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Flywheel Calibration of Coherent Doppler Wind Lidar

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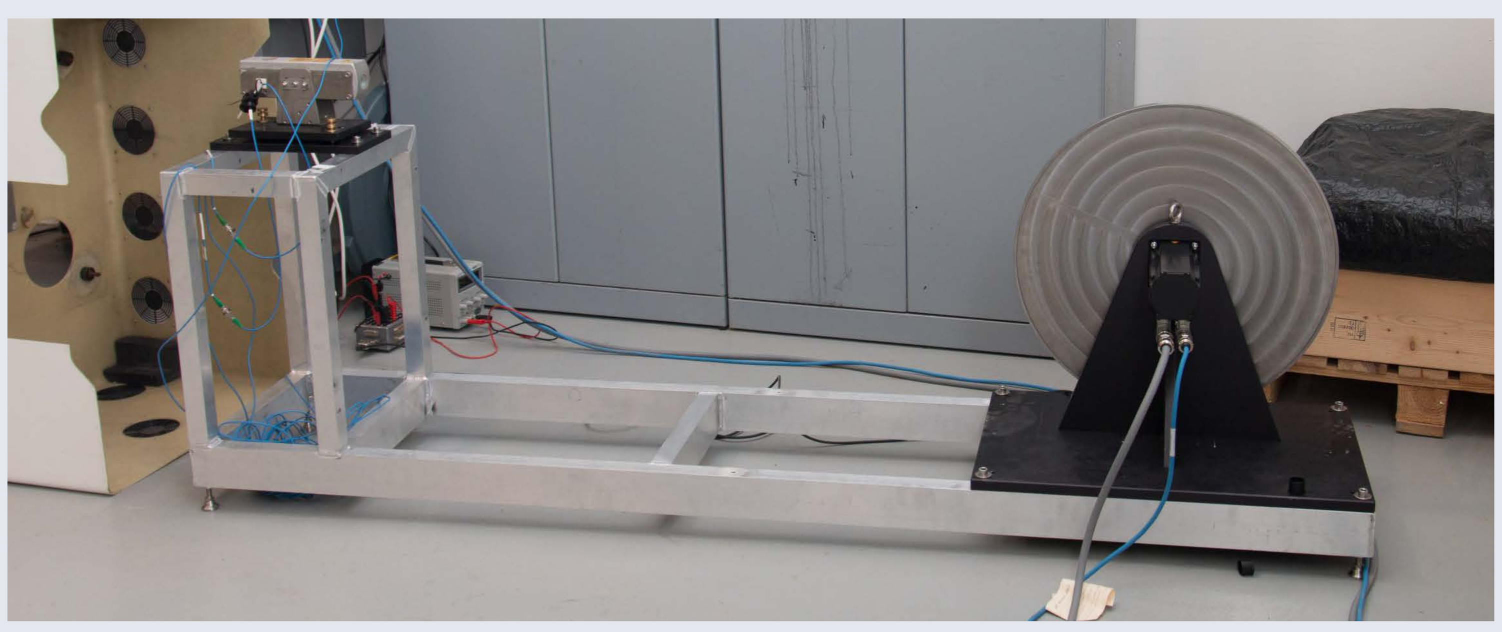
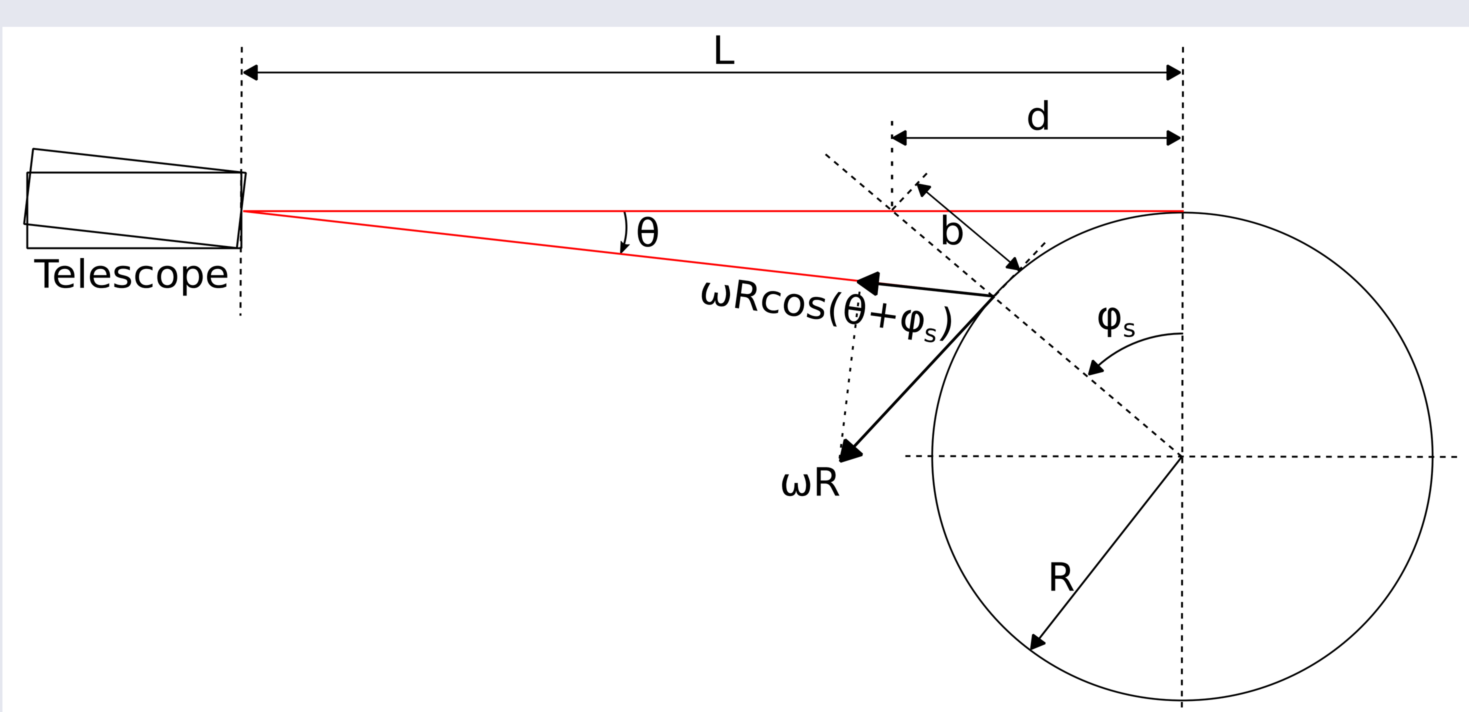
Motivation

"Lidars are absolute instruments" is a sentence often heard, and by that is meant, that given the laser wavelength and the sampling frequency, we are able to calculate the measured radial speed through the well-known equation: $V_r = \frac{1}{2}\lambda \cdot \Delta f$. There are no empirical constants that have to be found through a calibration as is the case for e.g. cups or even LDAs.
Why then do we claim that lidar calibration is necessary anyhow? Probably the most direct answer is that without a calibration we cannot know that the lidar is getting it right. There could be wrong constants or some subtle errors in the algorithm. Only by comparing to a known 'truth' can we be completely sure that the lidar gives the correct speed.

Calibration rig





- Stainless steel wheel: R = 286.76 mm
- Aluminium frame: L = 1.58 m
- Telescope: 1" aperture, f = 0.10 m
- Angular velocity measured by high resolution tachometer

Model

A simple model relating the error in measured speed due to non-tangential skimming angle, φ_s, to the inclination angle, θ, has been developed.

By assuming the laser beam is infinitely narrow and that θ and φ_s are both small, the relation between θ and φ_s can be found from simple geometrical considerations:

The tringle formed by the vertical radius, the length d, and back to centre is Pythagorean:

$$R^2 + d^2 = (R+b)^2 \approx (R+L\theta)^2.$$

Using that $L\theta \ll 2R$:

$$d^2 = 2RL\theta + L^2\theta^2 \approx 2RL\theta,$$

the skimming angle is found as:

$$\varphi_s \approx \sin\varphi_s \approx \frac{d}{R} = \sqrt{\frac{2L\theta}{R}}$$

Now, the lidar only measures the speed component along the line-of-sight, thus

$$V_{Lidar} = V_{Wheel} \cdot \cos(\varphi_s + \theta) \approx V_{Wheel} \cdot \cos(\varphi_s),$$

and by Taylor expansion of the cosine term a simple expression for the speed ratio error is reached

$$\frac{V_{Lidar}}{V_{Weel}} \approx 1 - \frac{\varphi_s^2}{2} = 1 - \frac{L\theta}{R}.$$

Finally, the speed ratio error sensitivity is given as

$$\frac{\partial\left(\frac{V_{Lidar}}{V_{Wheel}}\right)}{\partial\theta} = -\frac{L}{R}$$

which for the actual calibration rig becomes

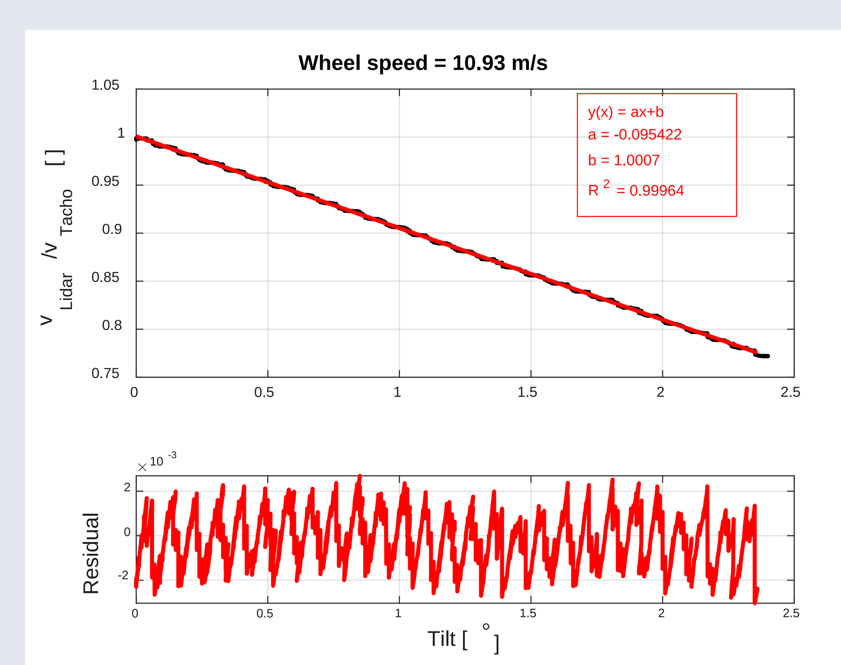
$$-\frac{L}{R} = \frac{1.58\ m}{0.287\ m} = -9.60\ \frac{\%}{°}$$

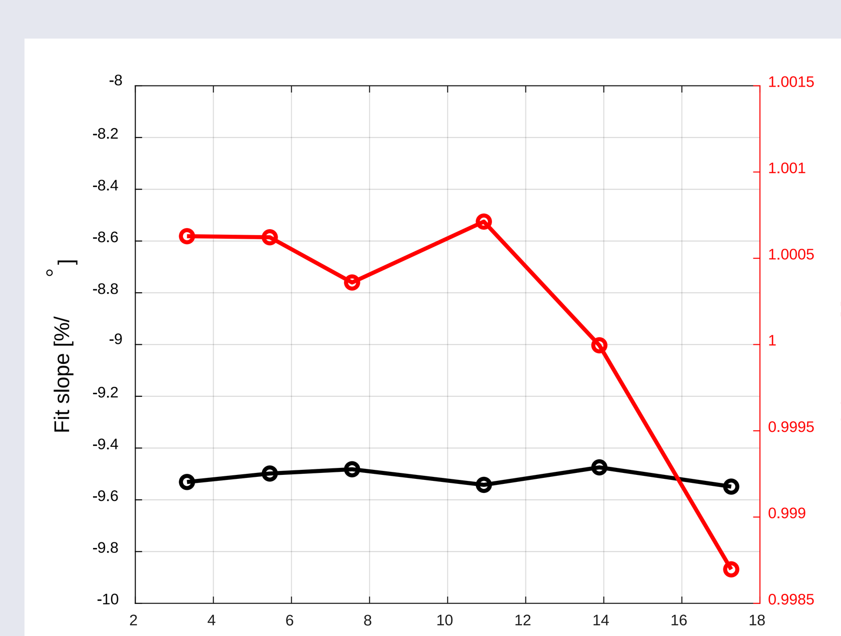
Main uncertainty components

- Wheel diameter: 0.1 mm
  - Relative uncertainty $u_r = \frac{0.1\ mm}{287\ mm} = 3.5 \cdot 10^{-4}$
- Frequency from tachometer to speed conversion: 10 ppm
  - Relative uncertainty $u_\omega = 1 \cdot 10^{-5}$
- Tilt angle resolution: 0.01°
  - Relative uncertainty $u_{\Delta\theta} = \frac{L}{R} \cdot \frac{\Delta\theta}{2} \cdot \frac{1}{\sqrt{3}} = 2.8 \cdot 10^{-4}$
- Combined relative uncertainty $u_{ref} = \sqrt{u_r^2 + u_\omega^2 + u_{\Delta\theta}^2} = 4.5 \cdot 10^{-4}$

Results

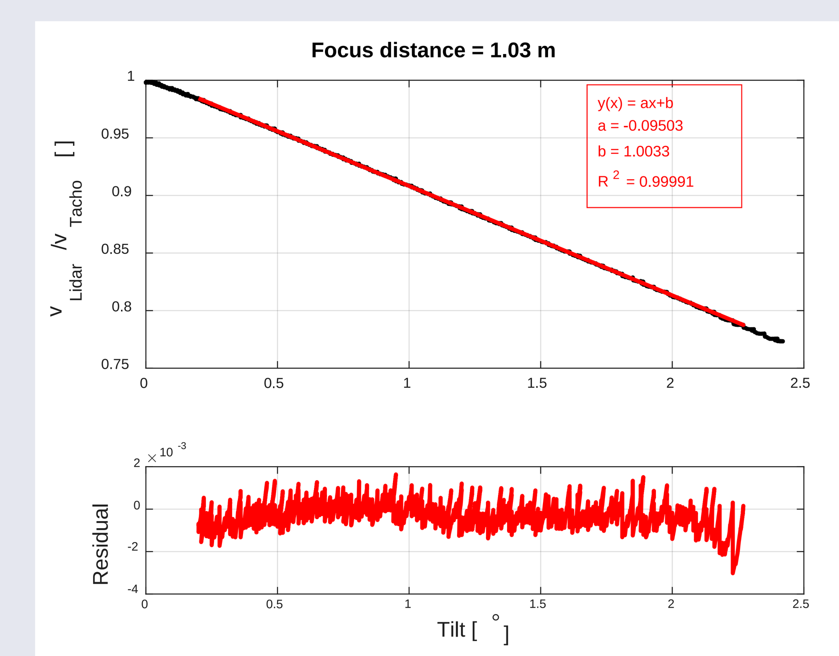
Function of speed

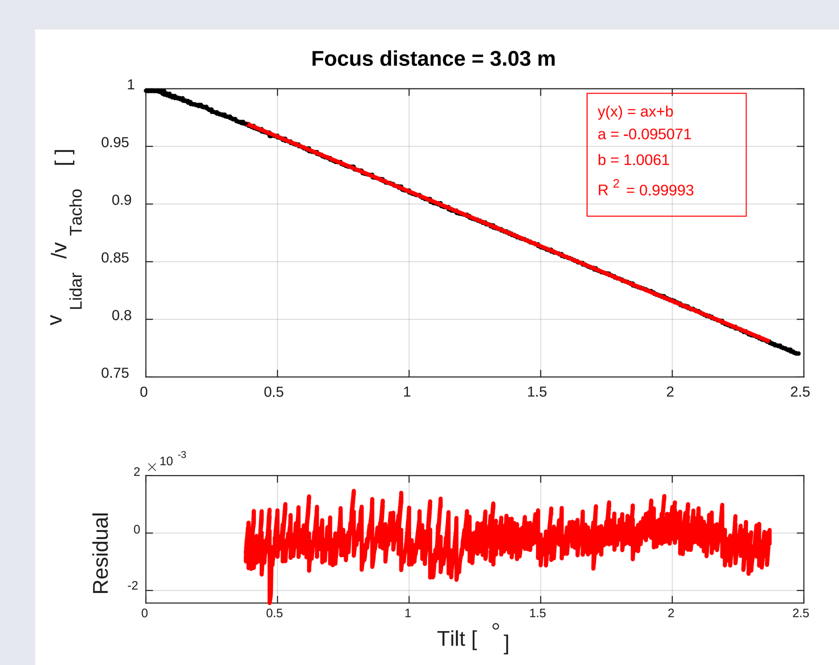


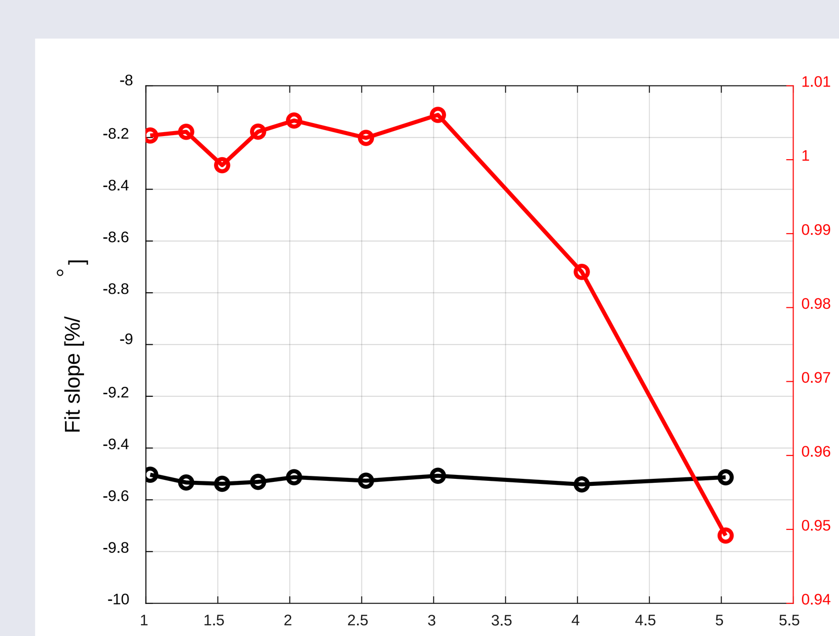


Top: Examples of calibration measurements at two reference speeds together with affine fit (red). The beam is focused the top of the wheel. Oscillations in the residual plots are due to the very narrow Doppler peak moving through the spectral bins alternatingly over- and underestimating the speed.
Bottom: Fit parameters (slope and intercept) as function of reference wheel speed

Function of focus distance







Top: Examples of calibration measurements at two different laser beam focus distances and thus different spot sizes at the wheel. The wheel speed is kept constant at 10.93 m/s.
Bottom: Fit parameters (slope and intercept) as function of focus distance

Conclusions

- Calibration rig built and running
- Model for measurement error as function of inclination angle made
- Measurements agree well with model
- Method stable over wide range of speeds
- The main uncertainties have been identified
- The line-of-sight speed can be calibrated to an uncertainty of approximately 0.5‰

DTU Wind Energy
Department of Wind Energy

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